PERFORMANCE ANALYSIS OF A PRE-FFT EQUALIZER DESIGN FOR DVB-T

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ABSTRACT

Conventional OFDM systems employ a guard interval to combat delay spread distortion of transmitted data. This reduces the efficiency of the OFDM transmission. A combined OFDM-Equalization reception strategy is presented in this paper. This strategy employs an Adaptive Equalizer to combat delay spread distortion instead of a guard interval. This facilitates the use of very short guard intervals and thus the transmission efficiency of the OFDM modulation scheme is improved. This paper presents the combined OFDM-equalization receiver and the pre-FFT equalizer designs. The efficiency of both the conventional OFDM and combined OFDM-equalization strategies is considered and it is demonstrated that combined OFDM-equalization offers a significant improvement in transmission efficiency. The transmission of OFDM signals in Single Frequency Networks is considered and it is shown that the combined OFDM-Equalization technique is particularly effective for such applications, offering an improvement in bandwidth efficiency of 14% under severe delay spread conditions. The limitations of the combined OFDM-equalization strategy to operate effectively under both additive noise and time variant conditions are considered. Performance is simulated and the sensitivity to this impairment analyzed.

I. INTRODUCTION

OFDM is the specified modulation method for the ETSI Terrestrial Digital Television Broadcast (DVB-T) standard [1]. Conventionally, OFDM employs a cyclic extension of transmitted OFDM symbols to combat delay spread distortion [2].

In this paper, a combined OFDM-equalization receiver incorporating a novel pre-FFT equalizer design [3] is proposed which allows for a considerable reduction in the length of the guard interval and thus offers a significant improvement in bandwidth efficiency.

Inter-Cell Interference in Single Frequency Networks (SFNs) manifests itself as very long delay spreads of the broadcast signal. This requires particularly long guard intervals for effective OFDM transmission. The use of long guard intervals reduces the efficiency of the modulation scheme. Efficiency can be improved by increasing the FFT size and thus the useful symbol length, but this requires an increase in computational complexity. The DVB-T standard specifies the use of either a 2048 point FFT ('2k mode') or an 8192 point FFT ('8k mode') [1]. The 8k mode is capable of supporting transmission under SFN conditions but requires more computation in both transmitter and receiver.

The pre-FFT Equalizer directly cancels delay spread effects and thus allows for the guard interval to be considerably shortened. This obviates the need to use higher numbers of sub-carriers and larger, more computationally demanding, FFTs.

This paper reviews the OFDM modulation process in section II and the conventional OFDM receiver in section III. The novel combined OFDM-equalization receiver is then presented in section IV and the pre-FFT equalizer is described in section V. The Efficiency of modulation for both conventional OFDM

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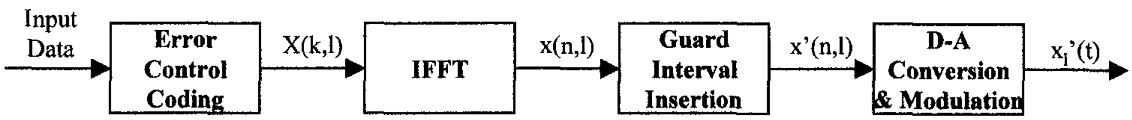

Figure 1. OFDM Modulation

and Combined OFDM-equalization receivers is considered in section VI. Section VII considers the combined OFDM-equalization technique's ability to operate under additive noise limitations and section VIII considers the performance under time variant channel conditions. In section IX, the benefits and limitations of the technique for application to Terrestrial Digital Video Broadcast are discussed.

II. OFDM TRANSMISSION

A conventional OFDM modulation process [2] - as illustrated in Figure 1 - is employed to generate the transmitted signal for reception by both conventional OFDM and combined OFDM equalization. A frequency domain input data vector, $X(k,l)$ consisting of N data symbols is input to an IFFT to produce a time domain vector, $x(n,l)$. (Here, k indexes the OFDM sub-band, n indexes the transmission symbol and l indexes the OFDM symbol.) The data and transmission symbol period is T_s and the OFDM symbol period is NT_s.

The time sequence is cyclically extended by M symbols to produce the transmission vector $x'(n,l)$. $x'(n,l)$ is up-sampled, D-A converted and RF modulated to produce the transmittable signal $x_l'(t)$.

The transmitted signal is distorted by delay spread and additive noise and the result is the received signal $y_l'(t)$.

For the purposes of this paper, no error control coding is applied at the transmitter.

III. THE CONVENTIONAL OFDM RECEIVER

The conventional OFDM receiver [2] is illustrated in Figure 2. The received signal $y_l'(t)$ is A-D converted at the receiver to produce the received vector $z'(n,l)$. The M symbols of $z'(n,l)$, which represent the cyclic extension, are discarded and an FFT is applied to produce $Z(k,l)$. $Z(k,l)$ is input to the channel compensator and $V(k,l)$ results. $V(k,l)$ is applied to a decision device to produce the output data, $W(k,l)$. The channel compensator takes the form of N single tap equalizers and its structure is illustrated in Figure 3 [2][4]. $S(k,l)$, the tap coefficients of the channel compensator are determined using data derived from pilots inserted into the transmitted signal [1][5][6].

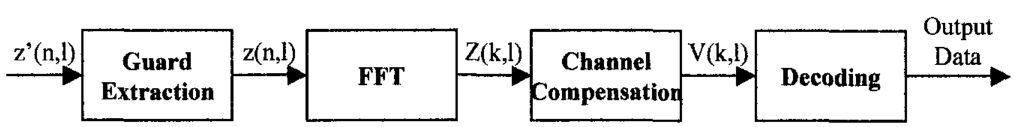

Figure 2. Conventional OFDM Receiver

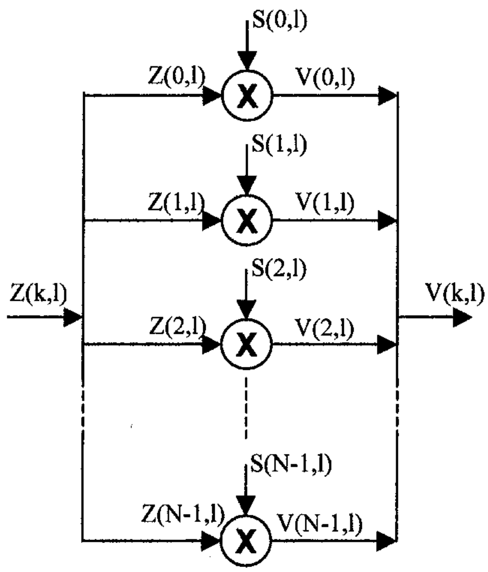

Figure 3. OFDM Channel Compensator

IV. THE COMBINED OFDM-EQUALIZATION RECEIVER

The structure of an OFDM receiver employing a pre-FFT Equalizer is shown in Figure 4. Its function can be seen to be that of a conventional OFDM receiver with the addition of the adaptive equalizing filter and a feedback loop.

$y'(n,l)$ is applied to the equalizing filter and $z'(n,l)$ results. The M symbols of $z'(n,l)$ which represent the cyclic extension are discarded and an FFT is applied to produce $Z(k,l)$. $Z(k,l)$ may be applied to a channel compensator to produce $V(k,l)$. However, if the pre-FFT equalizer is suitably adapted:

$$S(k,l) \approx 1 \qquad \text{for} \qquad 0 \le k \le N-1 \tag{1}$$

and

$$V(k,l) \approx Z(k,l) \tag{2}$$

$V(k,l)$ is applied to a decision device to produce the output data $W(k,l)$.

The feedback path in the receiver generates $w'(n,l)$ which is an estimate of the transmitted OFDM symbol, $x'(n,l)$ based on the post-decision output data symbols.

V. THE PRE-FFT EQUALIZER

The structure of the pre-FFT equalizer is shown in Figure 5. This design is similar to that of a Decision Feedback Equalizer (DFE) that might be used in a single carrier system [7]. An adaptation strategy combining the use of regular training sequences and decision directed adaptation can be employed.

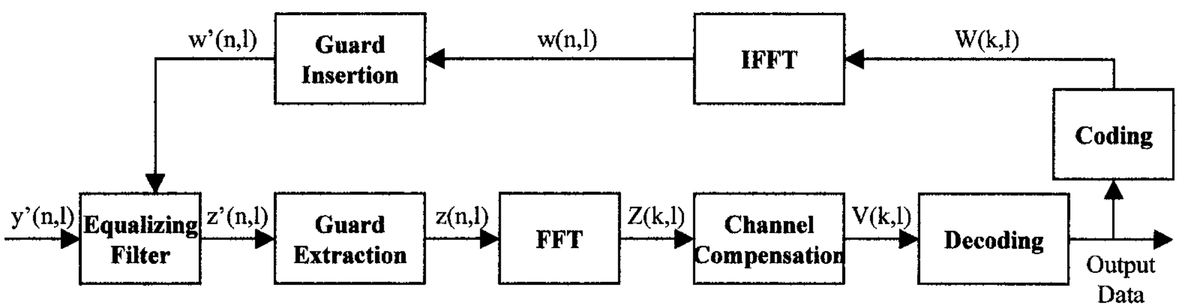

Figure 4. The Combined OFDM-equalization Receiver

The equalizer output is defined as:

$$z'(n,l)=\sum_{j=-J_1}^{-J_1+n} c(j)y'((n-j-(N+M)),l+1)+$$
$$\sum_{j=-J_1+n+1}^{0} c(j)y'((n-j),l)+C_{out}(n)\sum_{j=1}^{n} c(j)z'((n-j),l)+$$
$$\sum_{j=n+1}^{J_2} c(j)w'((n+(N+M)-j),l-1) \tag{3}$$

where:

$$C_{out}(n)=0 \quad \text{for} \quad n=0$$
$$C_{out}(n)=1 \quad \text{for} \quad n\neq 0 \tag{4}$$

Equalizer Training can be implemented in a conventional manner, such as by the LMS algorithm [8]. The LMS algorithm for the pre-FFT equalizer is described by:

$$c(j,n+1,l)=c(j,n,l)+\Delta\varepsilon'(n,l)y'^{*}((n-j-(N+M)),l+1)$$
$$\text{for } -J_1\leq j\leq -J_1+n+1 \tag{5}$$

$$c(j,n+1,l)=c(j,n,l)+\Delta\varepsilon'(n,l)y'^{*}((n-j),l)$$
$$\text{for } -J_1+n+2\leq j\leq 0 \tag{6}$$

$$c(j,n+1,l)=c(j,n,l)+\Delta\varepsilon'(n,l)x'^{*}((n-j),l)$$
$$\text{for } 1\leq j\leq n \tag{7}$$

$$c(j,n+1,l)=c(j,n,l)+$$
$$\Delta\varepsilon'(n,l)x'^{*}((n+(N+M)-j),l-1)$$
$$\text{for } n+1\leq j\leq J_2 \tag{8}$$

$$\varepsilon'(n,l)=x'(n,l)-z'(n,l) \tag{9}$$

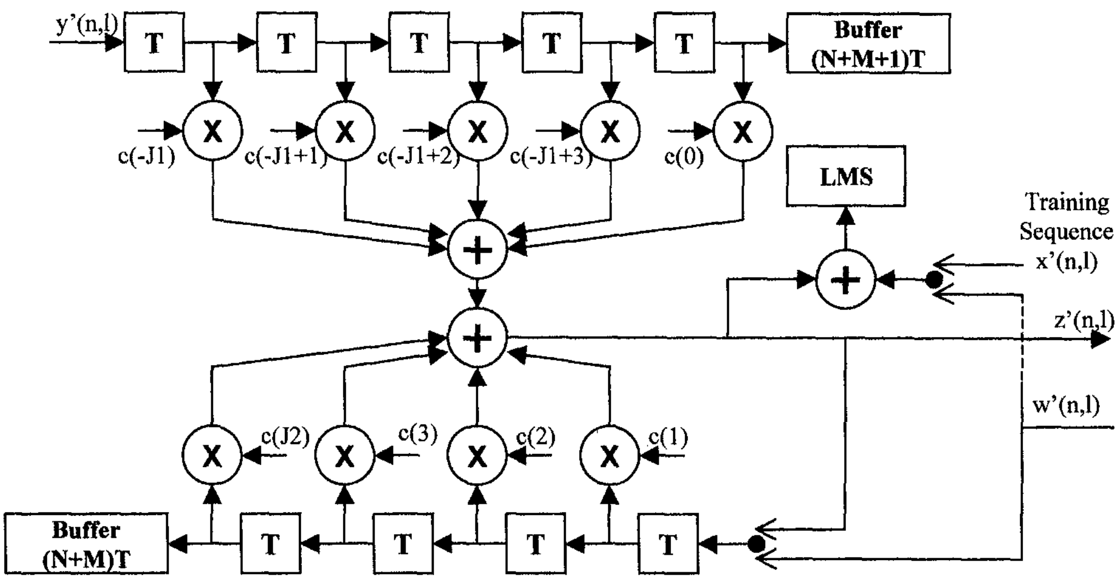

Figure 5. Pre-FFT Equalizer

Decision Directed Adaptation is made more complex by the parallel transmission nature of OFDM. Since a complete OFDM symbol must be received before it can be processed by the FFT and the decision device, the equalizer can only be updated at intervals of the OFDM symbol period [8]. Thus, at intervals of the OFDM symbol period the equalizer is adapted according to all the transmission sub-symbols for the preceding OFDM symbol. Also, it is necessary to input pre-decision symbols into the equalizer's feedback section until a complete OFDM symbol has been received and fed back to the equalizer. The LMS algorithm can be modified to adapt the equalizer in decision directed fashion and is now described by:

$$c(j,n,l+1)=c(j,n,l)+C_{ff}(j)\sum_{n=0}^{N+M+j-1}\Delta\varepsilon'(n,l)y'((n-j),l)+\sum_{n=N+M+j}^{N+M-1}\Delta\varepsilon'(n,l)y'((n-(N+M)-j),l+1)$$

$$\text{for} \quad -J_1 \le j \le 0 \tag{10}$$

$$c(j,n,l+1)=c(j,n,l)+\sum_{n=0}^{j-1}\Delta\varepsilon'(n,l)w'((n+(N+M)-j),l-1)+C_{fb}(j)\sum_{n=j}^{N+M-1}\Delta\varepsilon'(n,l)w'((n-j),l)$$

$$\text{for} \quad 1 \le j \le J_2 \tag{11}$$

$$\varepsilon'(n,l)=w'(n,l)-z'(n,l) \tag{12}$$

where:

$$C_{ff}(j)=0 \quad \text{for} \quad -j=N+M$$
$$C_{ff}(j)=1 \quad \text{for} \quad -j\neq N+M \tag{13}$$

$$C_{fb}(j)=0 \quad \text{for} \quad j=N+M$$
$$C_{fb}(j)=1 \quad \text{for} \quad j\neq N+M \tag{14}$$

As a result of feeding back pre-decision symbols into the equalizer, sensitivity to additive noise is increased.

VI. TRANSMISSION EFFICIENCY

Neglecting error control coding, the efficiency of the OFDM modulation scheme is defined as:

$$\varepsilon_{MOD}=\frac{N}{N+M} \tag{15}$$

VI.1. Efficiency of Conventional OFDM

The condition to prevent the occurrence of ICI in a conventional OFDM system is:

$$MT_s > \tau_{MAX+}+\tau_{MAX-} \tag{16}$$

where τ_{MAX+} and τ_{MAX-} are the longest delay and advance respectively (relative to the peak of the power delay profile) that occur in the radio channel.

From equations 15 and 16 it can be seen that the efficiency of a conventional OFDM system is limited according to:

$$\varepsilon_{CONV}<\frac{NT_s}{NT_s+(\tau_{MAX+}+\tau_{MAX-})} \tag{17}$$

Thus the efficiency of conventional OFDM is directly dependent upon the number of sub-carriers employed and the maximum delay spread occurring in the radio channel.

VI.2. Efficiency of Combined OFDM-Equalization

For a combined OFDM-Equalization system to prevent ICI, the equalizer must be suitably adapted. If a training sequence is employed at regular intervals, the transmission efficiency is:

$$\varepsilon_{COMB}=\varepsilon_{MOD}\varepsilon_{TRAIN} \tag{18}$$

where:

$$\varepsilon_{TRAIN}=\frac{L_{DD}}{L_{DD}+L_T} \tag{19}$$

where L_T and L_{DD} are the number of OFDM symbols forming the training sequence and the data sequence respectively. Since the guard interval is no longer required to prevent ICI, M will typically be very small and:

$$\varepsilon_{COMB}\approx\varepsilon_{TRAIN} \tag{20}$$

For ICI to be prevented it is also required that:

$$J_2 T_s > \tau_{MAX+} \tag{21}$$

$$J_1 T_s > \tau_{MAX-} \tag{22}$$

To determine the training sequence length required to suitably adapt the equalizer, the receiver has been simulated in software. Figure 6 shows the Mean Square Error (MSE) of the equalizer output plotted against the number of transmission symbols in the training sequence. $J_1 = J_2 = N + M$ is fixed and plots are shown for values of N from 64 to 2048. $M = 0$ in all cases. From Figure 6 it has been determined that, for these conditions, if $L_T \geq 5$, an MSE<10^{-1} can be achieved. Once an MSE below this threshold has been achieved decision directed adaptation can be employed.

Thus, more generally, to ensure that an MSE<10^{-1} is achieved during the training sequence it is required that:

$$L_T \geq \frac{5(J_1 + J_2)}{2(N + M)} \tag{23}$$

From equations 19 to 23 it can be seen that the efficiency of the combined-OFDM equalization technique is independent of the number of sub-bands employed in the modulation scheme. However, also from equations 19 to 23, it can be seen that the efficiency of the combined OFDM-equalization technique is dependent upon the delay spread of the radio channel, since, according to equations 21 and 22, increased delay spread necessitates increased numbers of equalizer taps and consequently (from equation 23) more iterations of the adaptation algorithm to achieve the same accuracy of adaptation. From equation 19 it is clear that the efficiency of the technique is improved as L_{DD} is increased. Since the value of L_T is determined by the delay spread conditions, the value of L_{DD} is now the dominant factor in determining the efficiency of transmission. The maximum value of L_{DD} which can be employed is limited only by the time variation of the radio channel.

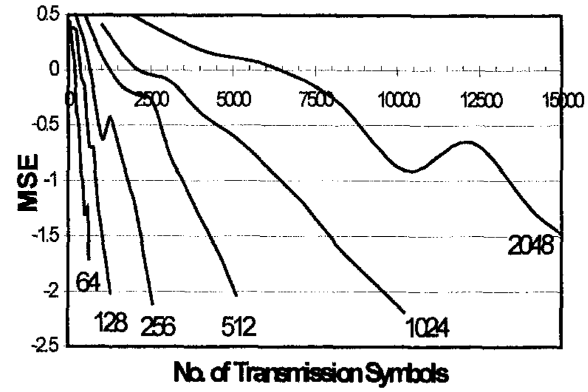

Figure 6. MSE vs. Number of Transmission Symbols

VI.3. Efficiency Comparison

To compare the efficiency of the conventional OFDM and combined OFDM equalization techniques, the efficiency of several strategies has been plotted as a function of the normalized maximum delay spread in Figure 7. The normalized maximum delay spread is defined as:

$$d_{MAX} = \frac{\tau_{MAX+} + \tau_{MAX-}}{T_s} \tag{24}$$

The efficiency of both conventional and combined techniques for both 2k and 8k modes is shown. For conventional OFDM a 1/4, 1/8, 1/16 or 1/32 guard interval is used as required. For the combined OFDM-equalization case, $L_{DD} = 100$ is assumed. A number of important points are illustrated in figure 7:

The conventional OFDM method is more efficient for small delays. This is due to the fact that the DVB-T specification only provides for a minimum 1/32 guard interval. The combined OFDM-equalization method suffers an efficiency penalty due to this guard interval as well as the training sequence requirements.

As is known, the 8k conventional method degrades more slowly than the 2k conventional method as the total delay period increases. However, the 2k combined method degrades more slowly than the 8k combined method. This is due to the greater degree of flexibility in the length of the training sequence facilitated by the shorter OFDM symbol.

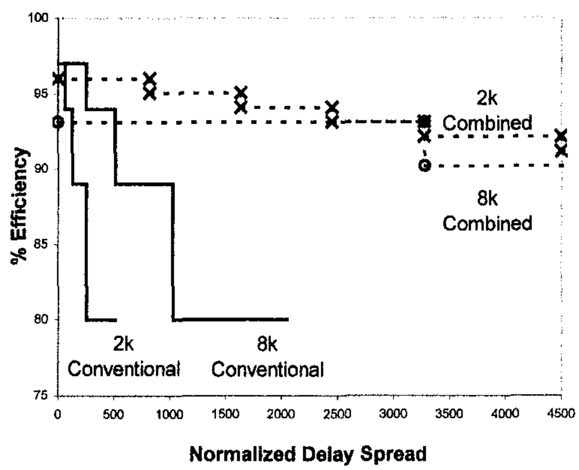

Figure 7. Transmission Efficiency

Most importantly, whether the 2k or 8k mode is used, the combined OFDM-Equalization strategy degrades much less rapidly than the conventional strategy as the normalized maximum delay spread increases. Further more, the largest normalized maximum delay spread that can be combated using the combined technique greatly exceeds that of the conventional technique – with no upper limit imposed as a result of the number of sub-carriers employed.

For a conventional, frequency divided, DVB-T network, the maximum delay period that is likely to occur is approximately 50μs ($d_{MAX} = 458$) [9]. Thus, a conventional OFDM system in 2k mode is capable of supporting transmission in such a network with a modulation efficiency of 80% in the worst case. In 8k mode, the conventional system can support transmission with a modulation efficiency of 97%. The combined OFDM-equalization technique is only capable of supporting an efficiency of 96%.

For a Single Frequency Network case the delay spread can rise to a typical 200μs ($d_{MAX} = 1829$) [9] for an antenna separation of 60km. Conventional OFDM in 2k mode cannot support transmission under these conditions within the DVB-T specification. In 8k mode, conventional OFDM can support transmission in an SFN but efficiency will typically only be 80%. In comparison, the efficiency of 2k combined OFDM-equalization only falls to around 94% for SFNs.

For SFNs with very large antenna spacing – 100km – delay spread can be as long as 300 μs ($d_{MAX} = 2743$). Conventional OFDM cannot operate under these conditions, even in 8k mode. Combined OFDM-equalization can operate in such a network with 94% transmission efficiency.

If the data rate is increased, the normalized delay spread for the same channel will also increase. Any future OFDM based systems that employ higher data rates than DVB-T in similar radio channels will gain even greater benefits from the combined OFDM-equalization technique.

VII. SENSITIVITY TO ADDITIVE NOISE

Due to the requirement to feed pre-decision symbols back into the pre-FFT equalizer's feedback section (see section V) the combined OFDM-equalization strategy suffers greater performance impairment due to additive noise. To assess sensitivity to additive noise, performance has been simulated in software for uncoded transmission over a wideband Rician channel. For this simulation, $J_1 = J_2 = N$. Figure 8 shows the MSE of the equalizer's output as a function of Signal to Noise Ratio using a QPSK symbol constellation and 64, 256 and 2048 sub-carriers. From figure 8 it can be seen that a MSE<10^{-1} can be achieved, provided that the SNR>23-30dB, depending upon the number of sub-carriers employed.

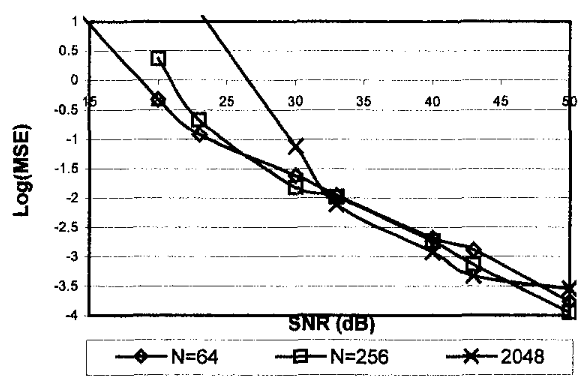

Figure 8. MSE vs SNR

VIII. SENSITIVITY TO TIME VARIATION

As described in section V, the combined OFDM-equalization strategy employs a modified version of the LMS algorithm to achieve decision directed adaptation. During decision directed adaptation the pre-FFT equalizer's taps are updated at the OFDM symbol period rather than the transmission period. As a result, the performance of the equalizer is sensitive to any significant variations in the radio channel's impulse response that occurs within the OFDM symbol period.

To assess this sensitivity, the equalizer's performance in tracking a time variant impulse response was simulated in software. The mobile channel simulated was wideband, with all paths varying according to independent Rayleigh distributions and the rate of variation determined according to the Doppler frequency. $J_1 = J_2 = N$ was fixed, $L_{DD} = 95$ and $L_T = 5$. The MSE of the equalizer's output is shown in Figure 9, plotted against the normalized Doppler frequency, $F_D T_s$. A QPSK symbol constellation was again employed.

The MSE results show a consistent trend with, as expected, a very low error for the static case ($F_d T_s = 0$), a rapid rise in error as the channel becomes mobile and a slower rise in error as mobility increases. Eventually, the error curves reach a critical point, beyond which the MSE rises very rapidly. This critical point represents the maximum Doppler frequency that can be supported by the pre-FFT equalizer for a given value of N. Above this value there is a high probability of the equalizer diverging due to significant changes in the channel's impulse response occurring within one OFDM symbol period. From Figure 9 it can be seen that the maximum normalized Doppler frequency that can be supported by the pre-FFT equalizer is:

$$(F_D T_s)_{MAX} \approx \frac{0.0025}{N} \tag{25}$$

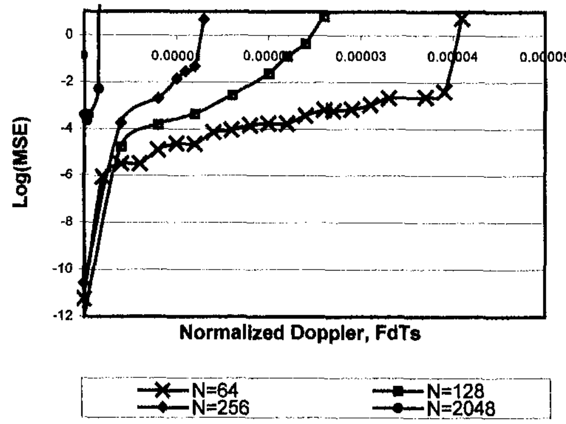

Figure 9. MSE vs. Normalized Doppler

Similar analysis has been undertaken in the past to assess the sensitivity of single carrier equalizer systems to mobile channel variation [10][11]. This analysis indicates that a single carrier equalizer can support a normalized Doppler frequency of approximately 0.003. Considering equation 25 and noting that $N = 1$ for a single carrier system it can be seen that there is a strong correlation between the results presented in this section and those published elsewhere.

IX. CONCLUSIONS

The pre-FFT equalizer can be designed to cancel the expected maximum delay spread. Thus, combining the pre-FFT equalizer with '2k' OFDM and the minimum 1/32 guard interval achieves a system which can combat a longer delay spread than '8k' carrier conventional OFDM with no increase in FFT complexity and potentially much improved bandwidth efficiency. Thus, an improvement of up to 14% can be achieved over conventional OFDM in channels with severe delays, such as those in a Single Frequency Network.

Due to the parallel transmission nature of OFDM some limitations are placed upon the function of the pre-FFT equalizer. The requirement to feed back pre-decision symbols in the equalizer necessitates that the SNR be sufficient to enable effective adaptation. The requirement to perform the modified LMS algorithm at intervals of the OFDM symbol period instead of the transmission symbol period results in a lower maximum rate of mobility than is the case for a single carrier system.

Provided that the limitations of SNR and mobility can be met, the Combined OFDM-equalization technique has the potential to improve the efficiency of SFN DVB-T compliant systems by as much as 14%. The technique also has the potential to provide even greater benefits for future, higher capacity systems.

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